Assessment of investment efficiency in a power system under performance-based regulation

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Abstract

The paper presents a new method for reliability investment decisions when a reward/penalty scheme is applied to the regulation of distribution system operators (DSOs). The method was developed in order to facilitate the transition from cost-based regulation (CBR) to performance-based regulation (PBR) for distribution utilities. New investment planning criteria for distribution utilities subjected to the new regulatory regime is identified and mathematically formulated as a new investment efficiency index IEI, which yields the relation between the improvement of system reliability due to the investment in the electric system and total investment costs. To determine the improvement of system reliability due to the investment in the electric network, the method uses the Monte Carlo (MC) simulation technique for the modeling of the stochastic nature of outages in electric networks, along with a linear program (LP), which enables us to calculate load flow equations under a fault state and provides information about power deficits in the electric system. The method was tested on Slovenian distribution systems, where several investment candidates were compared in order to determine which projects need to be undertaken in order to achieve the highest possible reliability increase.

Keywords

Power system reliability, investment planning, Monte Carlo simulation, linear programming.

1. Introduction

In deregulated and re-regulated electricity markets, regulatory authorities are increasingly adopting performance-based regulation (PBR) for distribution system operators (DSOs). A PBR regime provides distribution utilities with incentives for economic efficiency gains, and at the same time discourages them from sacrificing service reliability while pursuing these incentives. In order to satisfy these incentives, DSOs need new methods for distribution system planning due to new planning objectives under re-regulated electricity markets [1].

In the past, numerous methods for distribution system planning have been proposed [2]-[11]. The main goal of every method is to find an optimal solution to technical, economic and reliability issues. So far methods have mainly focused on technical and economic aspects of investment planning criteria. With the introduction of the reward/penalty scheme [12]-[17] in the regulation of DSOs, system reliability is gaining ground in investment planning.

Power system reliability can be evaluated using analytical and simulation techniques [18]-[25]. In the analytical approach the power system is represented by a mathematical model, and reliability indices are evaluated from this model using mathematical solutions [18]. Problems with the analytical approach occur when the system's complexity is high and assumptions are needed to simplify the model, which is due to the fact that simplifications often result in a loss of significance of the results [19]. When the system is more comprehensively modeled, simulation techniques are required for the evaluation of reliability indices [20]-[25]. In recent years reliability evaluations of power systems have been often conducted using the Monte Carlo (MC) simulation [20]-[25]. The MC simulation approach is a powerful tool that, compared to analytical methods, can handle more conditions related to reliability evaluation. Reference [23] further discusses advantages and disadvantages associated with both evaluation techniques.

In this paper, the MC simulation technique is used to determine the expected impacts of proposed investments on system reliability. Determination of changes in system reliability due to investments in electric power networks is especially important in regulatory regimes that use reward/penalty schemes to penalize and/or reward utilities based on their performance because of financial risk due to the uncertainty associated with maintaining a specific level of system reliability. Under such regulatory regimes new needs of the network planning process must be acknowledged and integrated in planning methodologies in order to achieve expected goals.

The importance of integrating new needs of the network planning process into planning methodologies have already been acknowledged by some authors [1], [5], [11]. Wu, Zheng and Wen [1] suggested a framework to clarify the interactions among various economic and engineering issues by reviewing the theoretical and practical progress in transmission investment and transmission planning methodology. Brown and Marshall [5] presented a budget constrained planning method, which incorporates accept/reject criteria for investment projects, that best allocates the capital budget while obtaining the highest possible system reliability. Their research was initiated because the use of reward/penalty schemes in the benchmarking of distribution utilities at some distribution utilities manifested in drastically reduced capital budgets. Financial risks defined by a quality regulation and distribution system reliability investment decisions under PBR were studied by Alvehag and Söder in [11], where a risk-based method for distribution system reliability investment decisions under PBR is proposed.

The contribution of this paper is a new method for reliability investment decisions when a reward/penalty scheme is applied to the regulation of DSOs. The incentive for distribution utilities in an incentive based regulation regime is given in the form of a reward/penalty scheme, where a sufficient level of system reliability is determined, and the reward or penalty of the distribution utilities depends on their quality relative to that sufficient level. Since system reliability is measured with system reliability indices, the main investment objective of distribution utilities under PBR regimes is a cost-effective improvement of those indices. To facilitate the transition from cost-based regulation (CBR) to PBR for distribution utilities, and to avoid the problems that follow a drastic reduction in capital budgets of distribution utilities that are unable to quickly adapt to the new regulatory regime described in [5], we propose a new investment planning method that uses the ratio between the improvement of the System Average Interruption Duration Index (SAIDI) due to the investment in the electric power network, and total costs of the investment as a measure of investment efficiency. Its main advantages compared to the similar existing solution presented in [5] are an exact mathematical formulation of the calculation of investment candidate benefits for power system reliability utilizing the MC simulation method, which is used for modeling the stochastic nature of outages in electric power systems, and a new investment efficiency index that provides a relation between investment costs and the improvement of the SAIDI index. The method can also prove useful to regulatory authorities when defining reward and penalty areas in the mathematical model of the reward/penalty payment structure, thus resulting in strong incentives for the regulation of DSOs.

The proposed method has been tested on the Slovenian distribution network where several investment candidates were compared based on their cost-efficient improvement of SAIDI. The paper also reports the obtained results.

The rest of the paper is organized as follows: regulation of DSOs is presented in Section 2. The methodology used to develop a method for the assessment of investment efficiency in electric power networks and the method itself are described in Section 3. Section 4 presents and discusses the results of the application of the proposed method for comparison of investment candidates for the Slovenian distribution network. Finally, Section 5 summarizes the main contributions of this paper.

2. Regulation of DSOs

For regulation of DSOs several regulation models have been developed in [12]-[17] which can be classified into two categories that represent CBR and PBR models, respectively. The general difference between the two regulation platforms is in the connection between the price of the service for customers and revenue as illustrated in Figure 1, [26]. While CBR schemes allow distribution utilities to charge their customers according to their costs plus some extra regulated profit, the link between price and revenue within the PBR schemes is weak since the revenue mainly depends on DSO’s performance which is a sequel of an ability to perform cost efficient investments that improve system’s reliability.

Recently PBR is gaining ground because the CBR allows DSOs to charge according to their costs presenting DSOs subjected to CBR very small incentive to be economically efficient. Since it is difficult for regulator to determine whether planned investments are justified or not, DSOs subjected to CBR also tend to over-invest rather than the opposite. Therefore, in order to increase cost efficiency of the DSOs, regulators are increasingly adopting PBR [13]. However the stronger the cost efficiency incentives are the greater is the need for quality regulation. Quality regulation in PBR is achieved through reward/penalty schemes which are used to reward the utilities for providing good reliability and penalize them for providing poor reliability, [14]. A common reward/penalty scheme is shown in Figure 2. Reward/penalty schemes usually comprise three areas: reward zone, dead zone and penalty zone. If distribution utility manages to obtain the level of system reliability in the dead zone neither a penalty nor a reward is assessed. On the other hand if the reliability is lower than the boundary of the dead zone, a penalty is assessed and if the reliability is greater than the dead zone boundary a reward is assessed.

Because revenue of DSOs subjected to PBR that incorporates reward/penalty scheme mainly depends on their ability to perform cost efficient investments that improve system's reliability, the objective of proposed investment planning method in this paper is to identify those investment candidates that achieve the greatest increment of system's reliability per monetary unit. Here SAIDI index is used as a measure of reliability as proposed in [19] and discussed in the subsequent text. The results of the method help DSOs to determine which investment candidates should be favored if available financial resources are insufficient to undertake all planned investments. Objective of proposed method is further discussed in Section 3.3.

3. Assessment of investment efficiency

The method for the assessment of investment efficiency proposed in this paper can be logically divided into three sections as shown in Figure 3. The initial step of the method represents the input data analysis that includes network modeling, load and generation forecasting and preparation of an investment plan that consists of different investment candidates. After the data preparation, the MC simulation is applied in order to produce a set of information about the effects of investment candidates on system load outages. The MC simulation is further discussed in Section 3.2. This data is then used to calculate SAIDI indices in the cost/benefit analysis. With the calculation of SAIDI indices, qualitative information about system reliability is obtained, allowing us to compare the reliability benefits of investment candidates. Since the method also deals with the economic aspect of investment planning, the final step in the process of investment efficiency assessment represents the calculation of the investment efficiency index (IEI). The IEI index was developed to evaluate the benefit of invested money on power system reliability, and is further discussed in Section 3.3. Input data preparation, the MC simulation and the cost/benefit analysis are described in detail in Sections 3.1, 3.2 and 3.3, respectively.

3.1. Input data preparation

The input data preparation process involves network modeling, load and generation forecasting and preparation of an investment plan that consists of different investment candidates. Network modeling and the preparation of an investment plan are essential to the input data preparation process and need to be accomplished very precisely because every inaccuracy has a direct impact on the simulated results of system reliability.

For the calculation of power flows the DC method was selected because the method for the assessment of investment efficiency is intended for use at the reliability investment planning stage where voltage support and reactive power management are of secondary importance. This is because the main focus is on improving power system reliability considering line overloading. The network model also incorporates element availabilities which are determined from historical data on the outages of elements in the power network for the previous regulatory period, and are later used in the MC simulation for the simulation of the stochastic nature of line and transformer outages, described in Section 3.2. Elements availabilities are calculated as follows:

$$A_r = \frac{m_r}{m_r + r_r}, \qquad (1)$$

where symbol A_r represents an availability of network element r, symbol m_r represents a mean time to failure of element r and symbol r_r represents a mean time to repair of element r.

Another important task in the input data preparation process is the preparation of the investment plan that consists of different investment candidates. Since investments in electric power networks affect the availability of new network elements used for the simulation of the stochastic nature of line and transformer outages in the MC simulation, changes in the availability of network elements caused by each proposed investment candidate need to be predicted. Elements' availability can be predicted using deterministic or heuristic methods.

The last part of the input data preparation process represents a forecasting of load and generation of active power, which is needed in the power flow calculations.

3.2. MC simulation

The network simulation in the method for the assessment of investment efficiency in electric power networks is performed utilizing the DC power flow method in combination with the linear programming (LP) optimization procedure. The main objective of the MC simulation is to produce a set of information needed to compare the technical benefits of investment candidates in the cost/benefit analysis described in Section 2.3. Since the comparison of technical benefits of investment candidates is based upon their improvement of SAIDI, which is calculated from load outage durations, the effects of each investment candidate on system load outages need to be simulated. Because the amount of remuneration for distribution utilities subjected to PBR depends on the values of reliability indices within a regulatory period, the simulation of the effects of investment candidates on load outages encompasses one regulatory period.

For simulation purposes, the discretization of the simulation period is necessary. With discretization, the simulation period is divided into a finite number of time intervals, where for each time interval a representative operation state of the power system needs to be determined. Operation states are determined using load and generation forecasts, which were prepared as part of the input data preparation process described in Section 3.1, and system element availabilities that are used to determine which elements in the simulated operation state are in service and which are not. For this purpose, a uniformly distributed random number RN_r from 0 to 1 is sampled for network element r in every iteration of the MC simulation. If the random number is less than the element's availability, the element in the simulated operation state is in service. Otherwise the network element in the simulated operation state is in outage. In the MC simulation, AE_{ij} is used to represent transmission line and transformer status, in which AE_{ij} = 1 indicates that the network element between nodes i and j is available, while AE_{ij} = 0 indicates otherwise. Consider the following example. A uniformly distributed random number from 0 to 1 is sampled for transmission line with an availability of 0.99. If the random number is less than 0.99, the unit is on outage. Otherwise the unit is in service.

A simulation of system behavior is performed utilizing a non-sequential MC simulation incorporating the DC power flow method in combination with the LP optimization procedure. The DC power flow method in combination with the LP technique enables us to simulate the system's behavior under a fault state. This is done by introducing slack variables in LP that cover the deficit of active power at load nodes caused by outages in the network. The slack variables need to engage only when without their usage no feasible solution exists, therefore the objective function J of LP is defined as:

$$min\, J = \sum_{i=1}^{n} s_i, \tag{2}$$

where symbol s_i represents the value of the slack variable at node i and symbol n represents the total number of nodes in the system. Another advantage of the LP technique is that it can enforce technical constraints of system elements when calculating power flow. This causes an activation of slack variables at load nodes when these constraints are violated, therefore the effects of outages caused by an overload of network elements can be considered in the simulation of system behavior. The constraints of LP defined by equations of the DC network model and technical constraints of system elements are as follows:

$$s_i + PG_i - PC_i + \sum_{j=1}^{n} \left(\frac{\delta_i - \delta_j}{X_{ij}} \right) = 0 \quad \forall \quad i = 1, ..., n, \quad \wedge \quad i \neq j, \tag{3}$$

$$\delta_1 = 0, \tag{4}$$

$$0 \le s_i \le PC_i \quad \forall \quad i = 1, \ldots, n, \tag{5}$$

$$\sum_{i=1}^{n} (s_i + PG_i) = \sum_{i=1}^{n} PC_i, \tag{6}$$

$$\min(P_{ij}) \cdot AE_{ij} \le P_{ij} \le \max(P_{ij}) \cdot AE_{ij} \quad \forall \quad i = 1, \ldots, n, \quad \forall \quad j = 1, \ldots, n, \quad \wedge \quad i \ne j. \tag{7}$$

The equality constraint (3) represents the DC model of the network comprising slack variables *s*, which cover the deficit of active power at load nodes when needed. Equation (4) sets the voltage angle of slack node to 0. Double inequality (5) ensures that all the slack variables are positive and that they can participate only in compensation of the deficit of active power at system nodes. Furthermore, double inequality (5) ensures that slack variable s_i cannot exceed consumption at node *i*. The balance between production and consumption of electric power, and enforcement of line limitations are achieved by equations (6) and (7), respectively.

Figure 4 provides a flowchart of the simulation procedure with the following steps:

- First, a network model and load measurements for a previous regulatory period are read.
- In the next step, the MC simulation enters into a loop where for all operational states according to a chosen discretization step load outages on the basis of network elements availabilities for the previous regulatory period are simulated. Operational states are defined using random generation of a number between 0 and 1 for each network element. If the random number is less than the element's availability, the element in the simulated operation state is in service. Otherwise the network element in the simulated operation state is in outage. In the MC simulation, AE_{ij} is used to represent transmission line and transformer status, in which $AE_{ij} = 1$ indicates that the network element between nodes *i* and *j* is available, while $AE_{ij} = 0$ indicates otherwise. The element's status is therefore defined as follows:

$$AE_{ij} = \begin{cases} 0\,; & \text{if} \quad RN_r < A_r \\ 1\,; & \text{if} \quad RN_r \ge A_r \end{cases}, \tag{8}$$

  where AE_{ij} represents the element status, RN_r represents randomly generated number and A_r represents element's availability.
- Power flows are calculated using a linear programming technique in combination with the DC power flow method. Linear programming enables a simple detection of load outages and enforcement of line limitations, as well.
- After all operational states of the previous regulatory period are simulated the same procedure is repeated for all investment candidates as it is shown in Figure 3. The only difference is that instead of load measurements for the previous regulatory period the load forecast for the next regulatory period is used and the network model is updated according to the investment candidate.

- When effects of all proposed investment candidates on load outages are simulated information about load outages are saved allowing us to conduct cost/benefit analysis, presented in Section 3.3.

3.3. Cost/Benefit analysis

The last part of the assessment of investment efficiency in electric networks where investment candidates are evaluated and compared represents the cost/benefit analysis. The evaluation of investment candidates comprises the effects of investments on system reliability and investment costs. The objective of the cost/benefit analysis is to rank investment candidates based on their improvement of SAIDI per monetary unit. Since the value of the distribution system's SAIDI for the previous regulatory period and the effects of different investment candidates on load outages for the subsequent regulatory period are simulated using the MC simulation technique, the improvement of SAIDI due to investment candidate *k* is calculated as follows:

$$\Delta SAIDI_k = \frac{\sum_{u=1}^{v}\sum_{i=1}^{n} PDD_{u,i,k} \cdot \Delta t}{NC} - SAIDI\,, \tag{9}$$

where:

$$PDD_{u,i,k} = \begin{cases} 0\,; & \text{if} \quad s_{u,i,k} = 0 \\ 1\,; & \text{if} \quad s_{u,i,k} > 0 \end{cases}. \tag{10}$$

In equations (9) and (10) $\Delta SAIDI_k$ represents the improvement of index SAIDI due to the investment candidate *k*, *v* represents the total number of simulated operation states, *n* represents the total number of nodes in the system, $s_{u,i,k}$ represents the slack variable at node *i* for simulated operational state *u* for investment candidate *k*, Δt represents the simulation time step, *NC* represents the total number of customers served and *SAIDI* represents the simulated value of index SAIDI for previous regulatory period. When the impacts of investment candidates on SAIDI are calculated, a comparison of investment candidates on the basis of their improvement of SAIDI per monetary unit is performed using the newly proposed investment efficiency index (IEI):

$$IEI_k = \frac{\Delta SAIDI_k}{C_k} \quad \forall \quad k = 1,\ \dots, IC, \tag{11}$$

where IEI_k represents the investment efficiency index for the investment candidate *k*, which is defined as a ratio between the improvement of index SAIDI due to the investment candidate *k* represented by a symbol $\Delta SAIDI_k$ and total costs of the investment candidate *k* represented by a symbol C_k and *IC* represents the total number of investment candidates.

In order to determine whether the IEI index is biased and to find the fairest way of comparison of investment candidates, the effects of investment candidates were also evaluated with some other indices which are presented below. The first index is the marginal cost index (MCI) and it is defined as follows:

$$MCI_k = \frac{C_k}{\Delta SAIDI_k} \quad \forall \quad k = 1, \ldots, IC, \tag{12}$$

where MCI_k represents the marginal cost index for the investment candidate k, which is defined as a ratio between the total costs of the investment candidate k, C_k, and the improvement of SAIDI due to the investment candidate k, $\Delta SAIDI_k$. The second index is the normalized investment efficiency index (NIEI) and is defined as follows:

$$NIEI_k = \frac{\Delta SAIDI_k / SAIDI}{C_k} \quad \forall \quad k = 1, \ldots, IC, \tag{13}$$

where $NIEI_k$ represents the normalized investment efficiency index for the investment candidate k, which is defined as a ratio between the normalized improvement of SAIDI due to the investment candidate k, $\Delta SAIDI_k/SAIDI$, and the total costs of the investment candidate k, C_k. The third index is the normalized marginal cost index (NMCI) and is defined as follows:

$$NMCI_k = \frac{C_k}{\Delta SAIDI_k / SAIDI} \quad \forall \quad k = 1, \ldots, IC, \tag{14}$$

where $NMCI_k$ represents the normalized marginal cost index for the investment candidate k, which is defined as a ratio between the total costs of the investment candidate k, C_k, and the normalized improvement of index SAIDI due to the investment candidate k, $\Delta SAIDI_k/SAIDI$.

Since the main objective of investing in distribution electric power network is to maintain or to improve the reliability level of energy supply with minimal costs, the objective of the proposed investment planning process is the maximization of the sum of IEIs or NIEIs and/or the minimization of the sum of MCIs and NMCIs of undertaken investments.

4. Case study

The proposed method described in Section 3 is tested on the part of the Slovenian distribution system where it is applied to evaluate and compare different investment candidates in order to determine which investment candidates should be favored when financial resources do not allow realizing all planned investments. A test system is shown in Figure 5. Even though the method is tested on the part of the Slovenian distribution system, the method is general and can be applied to any distribution system using different input data.

In this case study, 10 different investment candidates are considered presented in Table 1. It is presumed that available financial resources for investments amount to 100,000 €. Since some investment candidates exclude each other as they envisage different investments in the same section of the line, e.g. projects 1 and 2, 3 and 4, 6 and 7, and finally 8 and 9, their total investment costs depend on the combination of the projects which will be undertaken.

Therefore the total investment costs may vary from 97,347 € if the cheapest combination of all proposed investment candidates is selected and up to 199,011 € if the most expensive combination of all proposed investment candidates is selected. Obviously, the latter combination of investment candidates is not feasible, since the investment fund is limited to 100,000 €. ~~Investment candidates are as follows:~~

All investment candidates presented in Table 1 represent an enhancement of line availabilities since:

- underground cables are not exposed to severe weather conditions and have subsequently lower failure rates than uninsulated overhead lines,
- existing overhead lines are worn and therefore have higher failure rates than new overhead lines and
- installation of overhead ground wire greatly contributes to a decrease in the number of line faults by preventing direct hits to the power lines.

It should be emphasized that the proposed method only compares the investment candidates identified by DSO as needed projects according to criteria discussed in Section 2. The method does not propose new investment candidates.

In order to identify the effects of investment candidates on system reliability SAIDI indices for both distribution feeders for the previous regulatory period are simulated first. The simulated values of the two SAIDI indices are 117.72 min/Cus.yr for feeder A and 141.62 min/Cus.yr for feeder B. The simulated SAIDI indices differ from actual values for less than one minute per customer per year. Even greater accuracy, although at the expense of simulation time, can be achieved by shortening the simulation time step. In this case study a five second discretization was selected.

The next step in the assessment of investment efficiency is a simulation of the effects of investment candidates on load outages and consequently on SAIDI indices for both distribution feeders. This is achieved by the repetition of the system behavior simulation with modified line availabilities as predicted by the investment candidate. The results in Table 2 show that all investment candidates improve system reliability, since all investment candidates lower the value of SAIDI. Table 2 summarizes the comparison of investment candidates.

In order to show the advantage of the proposed method, two different investment strategies can be compared:

- **strategy A**: DSO does not apply the proposed method but the strategy is to maximize the number of undertaken investments within the available financial resource frame,
- **strategy B**: DSO invests in the projects with the highest investments efficiencies assessed by the proposed method.

In the first strategy, DSO would undertake investment candidates 10, 5, 9, 4, 7 and 2 since their total investment costs amount to 97,347 €. Selected investments improve SAIDI for 17.10 min/Cus.yr. IEI and total investment costs of all investment candidates are shown in Figure 6. Selected investment candidates are colored in black.

The second strategy follows the proposed method in order to identify which investment candidates should be selected to satisfy 100,000 € limit and to achieve the greatest investment efficiencies measured by the decrement of SAIDI allowed for in IEI, MCI, NIEI and NMCI indices. The results are shown in Figure 7 and Table 2. The order of investing should be as follows: 10, 6, 5, 1, 7, 8, 2, 3, 9, and 4. Selected investment candidates with the use of proposed method are colored in black in Figure 7. Since the investment candidates 6 and 7 exclude each other, the candidate 6 has a priority due to higher investment efficiency. The investment fund limited to 100,000 € shortens the list of the projects to: 10, 6, 5 and 8. Their total investment costs add up to 95,300 €. It should be noted, that the investment candidate 1 has a higher efficiency index comparing to the project 8, but it cannot be realized since the total investment costs would exceed the available fund. Selected investments improve SAIDI for 41.53 min/Cus.yr.

From the comparison of the results for the assessed strategies A and B summarized in Table 3 it can be concluded that the use of the proposed method leads to a higher improvement of reliability even though the number of realized investments is smaller. For interpretation of the results in Table 3 it is important to stress that higher IEIs and NIEIs present better investment efficiency, and on contrary, considering (12) and (14), lower MCIs and NMCIs lead to higher efficiency, as well. In addition, Figure 8 presents the ranking of the investment candidates for the analyzed test system. It can be noticed that all considered indices lead to the same ranking.

5. Conclusions

The paper proposes a new method for making reliability investment decisions when a reward/penalty scheme is applied to the regulation of DSOs. The method was developed in order to facilitate the transition from CBR to PBR for distribution utilities. Since the main objective of distribution utilities subjected to PBR is a cost-effective improvement of reliability indices, the transition from CBR to PBR introduces new investment planning criteria that need to be considered in taking investment planning decisions. In order to mathematically define these new planning criteria, we developed a new investment efficiency index, which yields a relation between the improvement of system reliability due to investment in electric system, and total investment costs. The improvement of system reliability due to investment is simulated using the MC simulation technique, which is used for the modeling of the stochastic nature of outages in electric power systems, and LP, which enables us to calculate load flow equations under a fault state and provides information about power deficits in the electric system.

The proposed method is applied to the part of the Slovenian distribution system in order to evaluate and compare different investment candidates, and to determine which investment candidates should be favored when financial resources are limited. Two investment strategies were considered: the simple one that strives to maximize the number of realized investments and the other that considers in a decision making procedure the investment efficiencies of the candidate projects obtained by the proposed method. The results show that in the first strategy 6 investment candidates are undertaken and SAIDI is improved for 17.10 min/Cus.yr. In the second strategy that applies the proposed method only 4 investment candidates are undertaken and SAIDI is improved for 41.53 min/Cus.yr. It can be concluded that the usage of the proposed investment planning method greatly improves DSOs investment efficiency resulting in a cost efficient improvement of system reliability. Besides this, in the PBR model where the reward/penalty scheme is applied to regulation of DSOs, the proposed method can maximize the reward by maximizing the improvement of SAIDIs.

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Figure captions

Figure 1: Difference between CBR and PBR
Figure 2: A common reward/penalty scheme
Figure 3: Flowchart for the assessment of the investment efficiency method
Figure 4: Flowchart of the simulation procedure
Figure 5: Test system used in case study
Figure 6: Total investment costs and IEI indices of investment candidates in strategy A
Figure 7: Total investment costs and IEI indices of investment candidates in strategy B
Figure 8: Comparison of investment efficiency indices

Table captions

Table 1: Investment candidates
Table 2: Comparison of investment candidates
Table 3: Comparison of different investment strategies

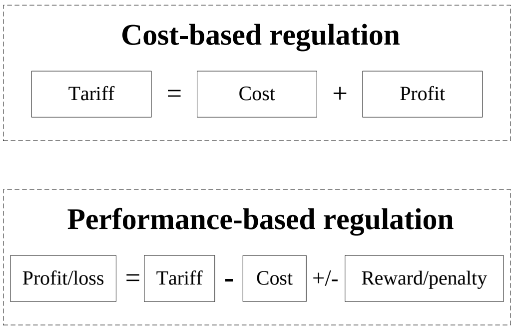

Figure 1: Difference between CBR and PBR

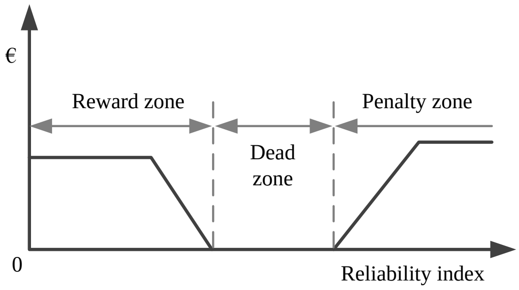

Figure 2: A common reward/penalty scheme

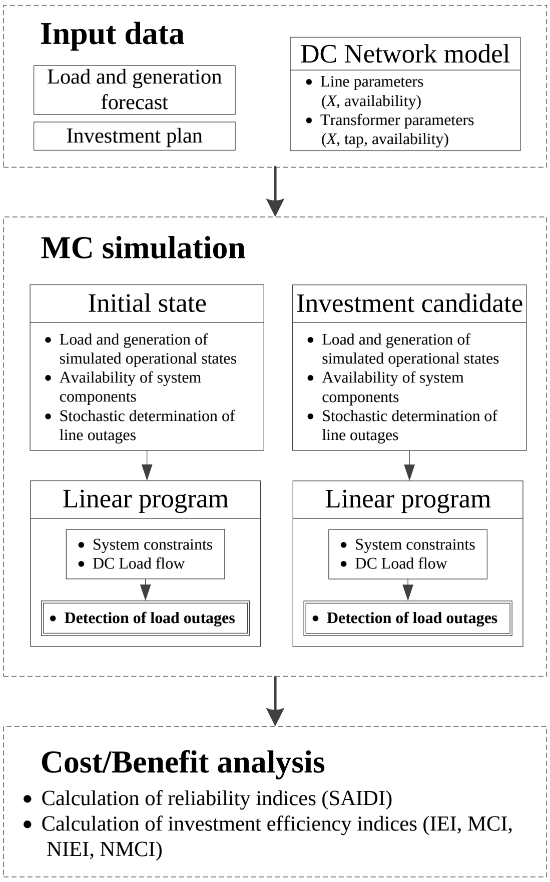

Figure 3: Flowchart for the assessment of the investment efficiency method

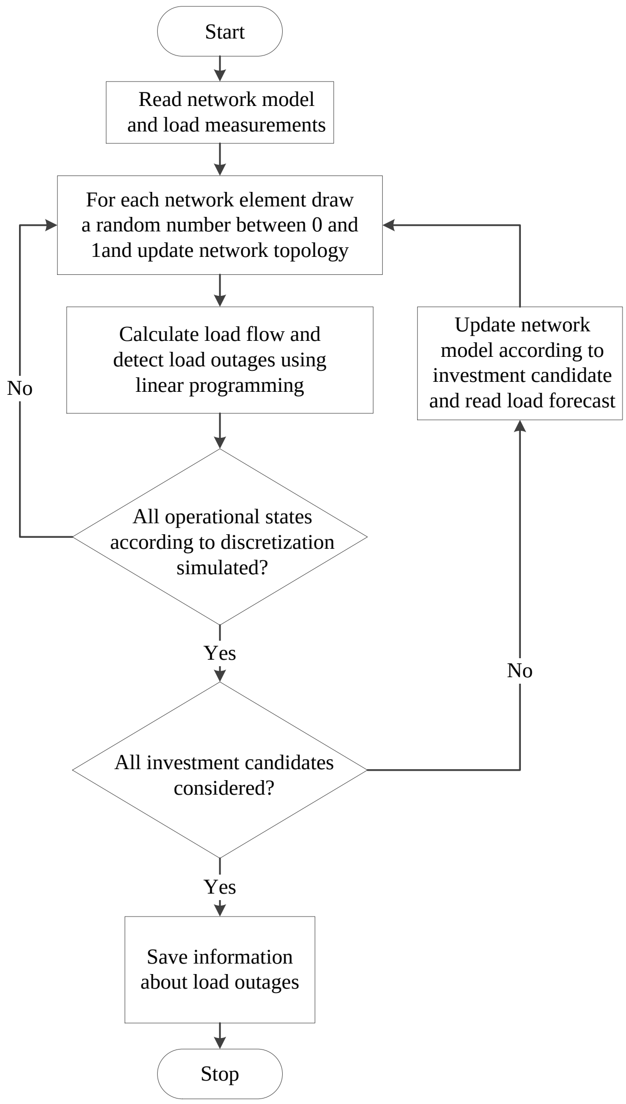

Figure 4: Flowchart of the simulation procedure

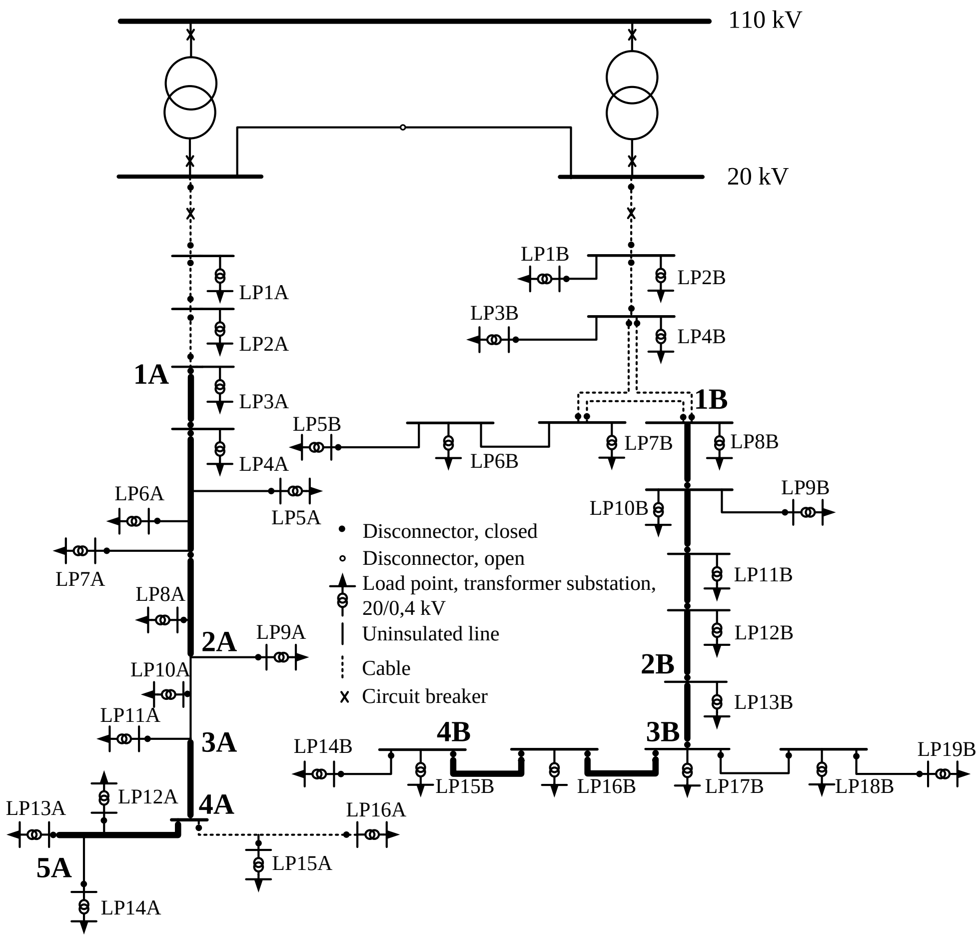

Figure 5: Test system used in case study

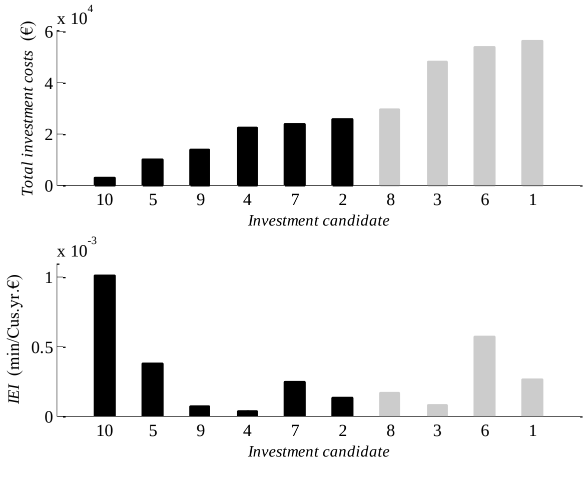

Figure 6: Total investment costs and IEI indices of investment candidates in strategy A

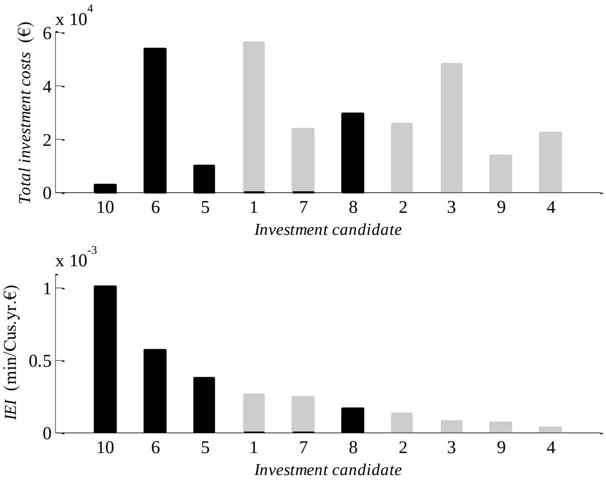

Figure 7: Total investment costs and IEI indices of investment candidates in strategy B

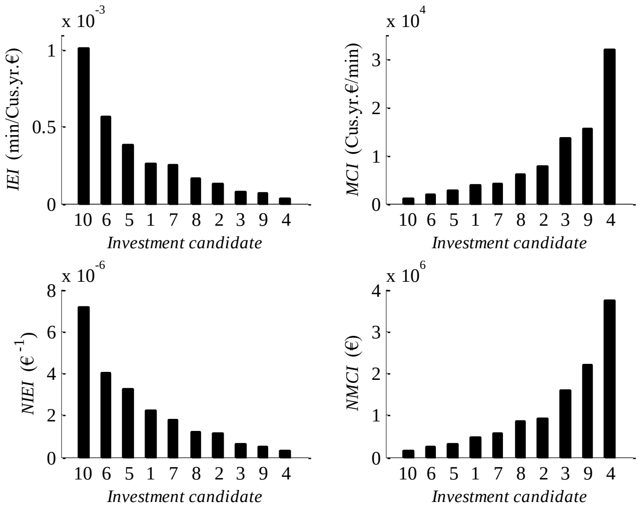

Figure 8: Comparison of investment efficiency indices

Table 1: Investment candidates

ID	Investment	Location	Investment costs [€/km]
1	Replacement with new 1,5 km underground cable	1A-2A	37,000
2	Replacement with new 1.5 km overhead line	1A-2A	17,000
3	Replacement with new 1.3 km underground cable	4A-5A	37,000
4	Replacement with new 1.3 km overhead line	4A-5A	17,000
5	Installation of 1.2 km of overhead ground wire	3A-4A	8,000
6	Replacement with new 1.4 km underground cable	1B-2B	37,000
7	Replacement with new 1.4 km overhead line	1B-2B	17,000
8	Replacement with new 0.8 km underground cable	3B-4B	37,000
9	Replacement with new 0.8 km overhead line	3B-4B	17,000
10	Installation of 0.3 km of overhead ground wire	2B-3B	8,000

Table 2: Comparison of investment candidates

FEEDER A					
Investment candidate	1	2	3	4	5
Actual SAIDI [min/Cus.yr]	117.72	117.72	117.72	117.72	117.72
Simulated SAIDI (before investing) [min/Cus.yr]	117.18	117.18	117.18	117.18	117.18
Simulated SAIDI (after investing) [min/Cus.yr]	102.59	113.88	113.66	116.49	113.43
Total investment costs [€]	55,833	25,500	47,878	21,998	9,936
IEI [min/Cus.yr.€]	**2.61e-04**	**1.29e-04**	**7.35e-05**	**3.14e-05**	**3.77e-04**
MCI [€Cus.yr/min]	**3,827**	**7,727**	**13,602**	**31,881**	**2,650**
NIEI [$€^{-1}$]	**2.23e-06**	**1.10e-06**	**6.27e-07**	**2.68e-07**	**3.22e-06**
NMCI [€]	**448,424**	**905,482**	**1,593,848**	**3,735,834**	**310,480**
FEEDER B					
Investment candidate	6	7	8	9	10
Actual SAIDI [min/Cus.yr]	141.62	141.62	141.62	141.62	141.62
Simulated SAIDI (before investing) [min/Cus.yr]	140.86	140.86	140.86	140.86	140.86
Simulated SAIDI (after investing) [min/Cus.yr]	110.57	135.02	136.02	139.99	138.21
Total investment costs [€]	53,391	23,800	29,341	13,481	2,632
IEI [min/Cus.yr.€]	**5.67e-04**	**2.45e-04**	**1.65e-04**	**6.45e-05**	**1.01e-03**
MCI [€Cus.yr/min]	**1,763**	**4,075**	**6,062**	**15,495**	**993**
NIEI [$€^{-1}$]	**4.03e-06**	**1.74e-06**	**1.17e-06**	**4.58e-07**	**7.15e-06**
NMCI [€]	**248,288**	**574,053**	**853,920**	**2,182,682**	**139,903**

Table 3: Comparison of different investment strategies

Investment strategy	**Strategy A** Maximization of realized investments	**Strategy B** The use of proposed method
Investment fund [€]	100,000	100,000
Improvement of SAIDI [min/Cus.yr]	17.10	41.53
Number of realized investments	6	4
$\sum_{k=1}^{IC} IEI_k$ **[min/Cus.yr.€]**	**1.85e-03**	**2.12e-03**
$\sum_{k=1}^{IC} MCI_k$ **[€Cus.yr/min]**	**61,829**	**11,468**
$\sum_{k=1}^{IC} NIEI_k$ **[$€^{-1}$]**	**1.39e-05**	**1.56e-05**
$\sum_{k=1}^{IC} NMCI_k$ **[€]**	**7,848,435**	**1,552,592**